Full-field optical methods for mechanical engineering: essential concepts to find one' way

Yves Surrel

Techlab

September 2004

Contents

1 Introduction

- Large variety of techniques.
- Terminology issue (structured light, fringe projection, electronic speckle pattern interferometry, shearography, TV holography. . .).
- Some keys for a systematic sorting:
  - ✓ white light or laser light;
  - ✓ nature of information encoding (carrier, random)
  - ✓ light/surface interaction (reflection,diffraction,diffusion)
  - ✓ interfering beams
- Surface techniques

1 Introduction

- Large variety of techniques.
- Terminology issue (structured light, fringe projection, electronic speckle pattern interferometry, shearography, TV holography. . .).
- Some keys for a systematic sorting:
  - ✓ white light or laser light;
  - ✓ nature of information encoding (carrier, random)
  - ✓ light/surface interaction (reflection,diffraction,diffusion)
  - ✓ interfering beams
- Surface techniques

1 Introduction

- Large variety of techniques.
- Terminology issue (structured light, fringe projection, electronic speckle pattern interferometry, shearography, TV holography. . .).
- Some keys for a systematic sorting:
  - ✓ white light or laser light;
  - ✓ nature of information encoding (carrier, random)
  - ✓ light/surface interaction (reflection,diffraction,diffusion)
  - ✓ interfering beams
- Surface techniques

1 Introduction

- Large variety of techniques.
- Terminology issue (structured light, fringe projection, electronic speckle pattern interferometry, shearography, TV holography. . .).
- Some keys for a systematic sorting:
  - ✓ white light or laser light;
  - ✓ nature of information encoding (carrier, random)
  - ✓ light/surface interaction (reflection,diffraction,diffusion)
  - ✓ interfering beams
- Surface techniques

1 Introduction

- Large variety of techniques.
- Terminology issue (structured light, fringe projection, electronic speckle pattern interferometry, shearography, TV holography. . .).
- Some keys for a systematic sorting:
  - ✓ white light or laser light;
  - ✓ nature of information encoding (carrier, random)
  - ✓ light/surface interaction (reflection,diffraction,diffusion)
  - ✓ interfering beams
- Surface techniques

1 Introduction

- Large variety of techniques.
- Terminology issue (structured light, fringe projection, electronic speckle pattern interferometry, shearography, TV holography. . .).
- Some keys for a systematic sorting:
  - ✓ white light or laser light;
  - ✓ nature of information encoding (carrier, random)
  - ✓ light/surface interaction (reflection,diffraction,diffusion)
  - ✓ interfering beams
- Surface techniques

1 Introduction

- Large variety of techniques.
- Terminology issue (structured light, fringe projection, electronic speckle pattern interferometry, shearography, TV holography. . .).
- Some keys for a systematic sorting:
  - ✓ white light or laser light;
  - ✓ nature of information encoding (carrier, random)
  - ✓ light/surface interaction (reflection,diffraction,diffusion)
  - ✓ interfering beams
- Surface techniques

1 Introduction

- Large variety of techniques.
- Terminology issue (structured light, fringe projection, electronic speckle pattern interferometry, shearography, TV holography. . .).
- Some keys for a systematic sorting:
  - ✓ white light or laser light;
  - ✓ nature of information encoding (carrier, random)
  - ✓ light/surface interaction (reflection,diffraction,diffusion)
  - ✓ interfering beams
- Surface techniques

2 White light methods

Can often be called geometrical methods (optics are generally restricted to image formation). Physical phenomena allowing the measurement are geometrical: deformation of a surface pattern, triangulation etc

2.1 Random encoding

A random pattern (local signature) will allow to match pairs of points between the initial and final stages: there is no quantitative information.

- ☞ digital image correlation for displacement measurments;
- ☞ stereocorrelation ($\Longleftrightarrow$ stereophotogrammetry; principle is the same, only implementation is different) : 2 cameras + triangulation $\Longrightarrow$ mesure 3D;
- ☞ speckle intensity correlation (the speckle is the signal)

2 White light methods

Can often be called geometrical methods (optics are generally restricted to image formation). Physical phenomena allowing the measurement are geometrical: deformation of a surface pattern, triangulation etc

2.1 Random encoding

A random pattern (local signature) will allow to match pairs of points between the initial and final stages: there is no quantitative information.

- ☞ digital image correlation for displacement measurments;
- ☞ stereocorrelation ($\Longleftrightarrow$ stereophotogrammetry; principle is the same, only implementation is different) : 2 cameras + triangulation $\Longrightarrow$ mesure 3D;
- ☞ speckle intensity correlation (the speckle is the signal)

2 White light methods

Can often be called geometrical methods (optics are generally restricted to image formation). Physical phenomena allowing the measurement are geometrical: deformation of a surface pattern, triangulation etc

2.1 Random encoding

A random pattern (local signature) will allow to match pairs of points between the initial and final stages: there is no quantitative information.

☞ digital image correlation for displacement measurments;

☞ stereocorrelation ($\Longleftrightarrow$ stereophotogrammetry; principle is the same, only implementation is different) : 2 cameras + triangulation $\Longrightarrow$ mesure 3D;

☞ speckle intensity correlation (the speckle is the signal)

Figure 1: Speckle pattern

Possible random pattern markings:

- the material itself can be textured by itself heterogeneous materials, fabrics, microstructures, rugosity);
- the surface must be marked: light paint spray or laser light speckle;
- in both preceding cases, the pattern is attached to the surface: 3D displacements can be measured;
- the diffusive surface can be immersed in a coding volume (e.g. videoprojector displaying a random pattern); only shape and shape variation can be measured;

Possible random pattern markings:

- the material itself can be **textured** by itself heterogeneous materials, fabrics, microstructures, rugosity);
- the surface must be marked: light paint spray or laser light speckle;
- in both preceding cases, the pattern is **attached** to the surface: 3D displacements can be measured;
- the diffusive surface can be immersed in a **coding volume** (e.g. videoprojector displaying a random pattern); only shape and shape variation can be measured;

Possible random pattern markings:

- the material itself can be textured by itself heterogeneous materials, fabrics, microstructures, rugosity);
- the surface must be marked: light paint spray or laser light speckle;
- in both preceding cases, the pattern is attached to the surface: 3D displacements can be measured;
- the diffusive surface can be immersed in a coding volume (e.g. videoprojector displaying a random pattern); only shape and shape variation can be measured;

Possible random pattern markings:

- the material itself can be textured by itself heterogeneous materials, fabrics, microstructures, rugosity);
- the surface must be marked: light paint spray or laser light speckle;
- in both preceding cases, the pattern is attached to the surface: 3D displacements can be measured;
- the diffusive surface can be immersed in a coding volume (e.g. videoprojector displaying a random pattern); only shape and shape variation can be measured;

2.2 Carrier modulation encoding

The information is in the phase modulation of a temporal or spatial carrier: it is a quantitative information. The measurand is related (linearly or not) to the phase. Phase-stepping methods are routine. Less than $2\pi/500$ resolution is common.

- ☞ Displacement measurement: grid method ;
- ☞ moiré: add-on to the grid method: frequency shift through a beat between grids;
- ☞ shape measurement: 2 cameras + triangulation; $\Longrightarrow$ 3D measurement;
- ☞ deflectometry: measurement of displacements in the *reflected image of a grid*: measurement of local slopes.

2.2 Carrier modulation encoding

The information is in the phase modulation of a temporal or spatial carrier: it is a quantitative information. The measurand is related (linearly or not) to the phase. Phase-stepping methods are routine. Less than $2\pi/500$ resolution is common.

- Displacement measurement: grid method ;
- moiré: add-on to the grid method: frequency shift through a beat between grids;
- shape measurement: 2 cameras + triangulation; $\Longrightarrow$ 3D measurement;
- deflectometry: measurement of displacements in the *reflected image of a grid*: measurement of local slopes.

2.2 Carrier modulation encoding

The information is in the phase modulation of a temporal or spatial carrier: it is a quantitative information. The measurand is related (linearly or not) to the phase. Phase-stepping methods are routine. Less than $2\pi/500$ resolution is common.

- ☞ Displacement measurement: grid method ;
- ☞ moiré: add-on to the grid method: frequency shift through a beat between grids;
- ☞ shape measurement: 2 cameras + triangulation; $\Longrightarrow$ 3D measurement;
- ☞ deflectometry: measurement of displacements in the *reflected image of a grid*: measurement of local slopes.

2.2 Carrier modulation encoding

The information is in the phase modulation of a temporal or spatial carrier: it is a quantitative information. The measurand is related (linearly or not) to the phase. Phase-stepping methods are routine. Less than $2\pi/500$ resolution is common.

- Displacement measurement: grid method ;
- moiré: add-on to the grid method: frequency shift through a beat between grids;
- shape measurement: 2 cameras + triangulation; $\Longrightarrow$ 3D measurement;
- deflectometry: measurement of displacements in the *reflected image of a grid*: measurement of local slopes.

2.2.1 Examples: displacement measurements

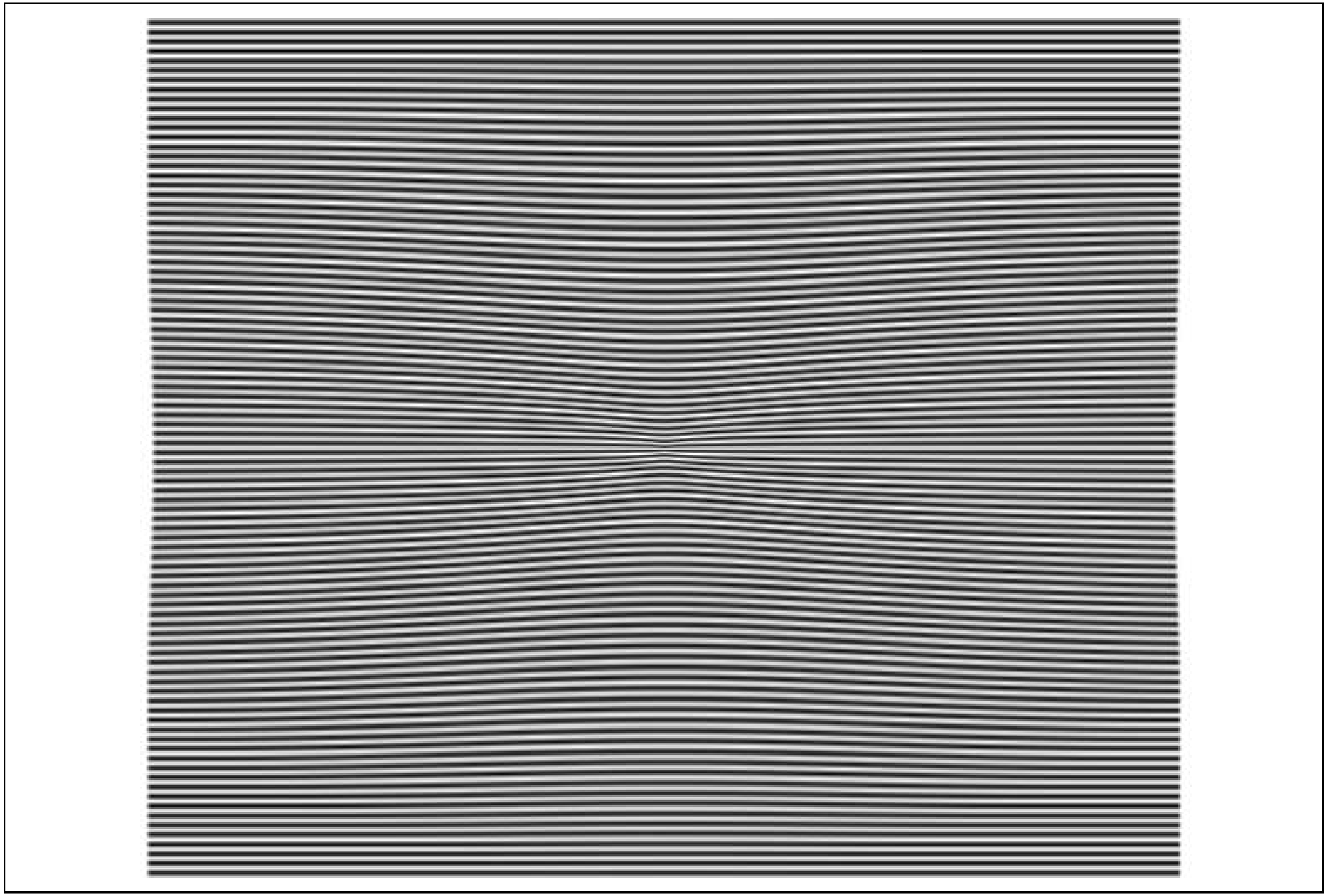
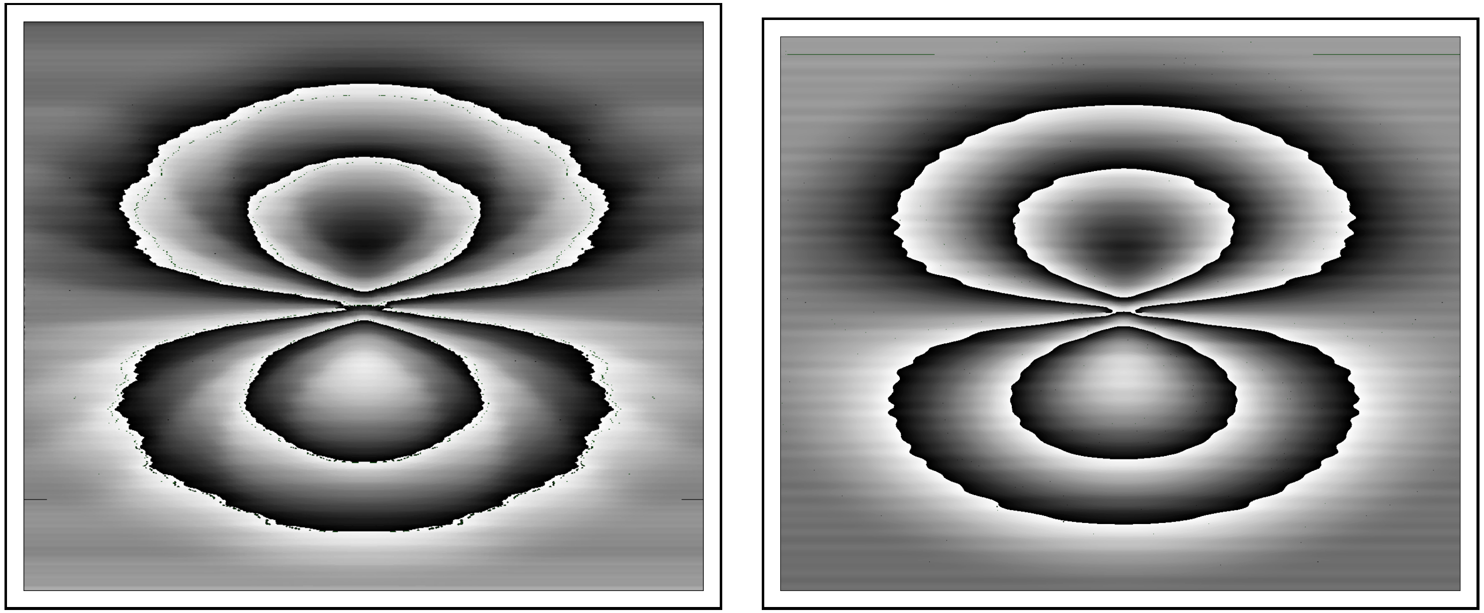


Figure 2: Distorsion of a grid: frequency or phase modulation

Figure 3: Moiré fringes



(a) . . . the moiré pattern

(b) . . . the grid

Figure 4: Phase maps obtained from. . .

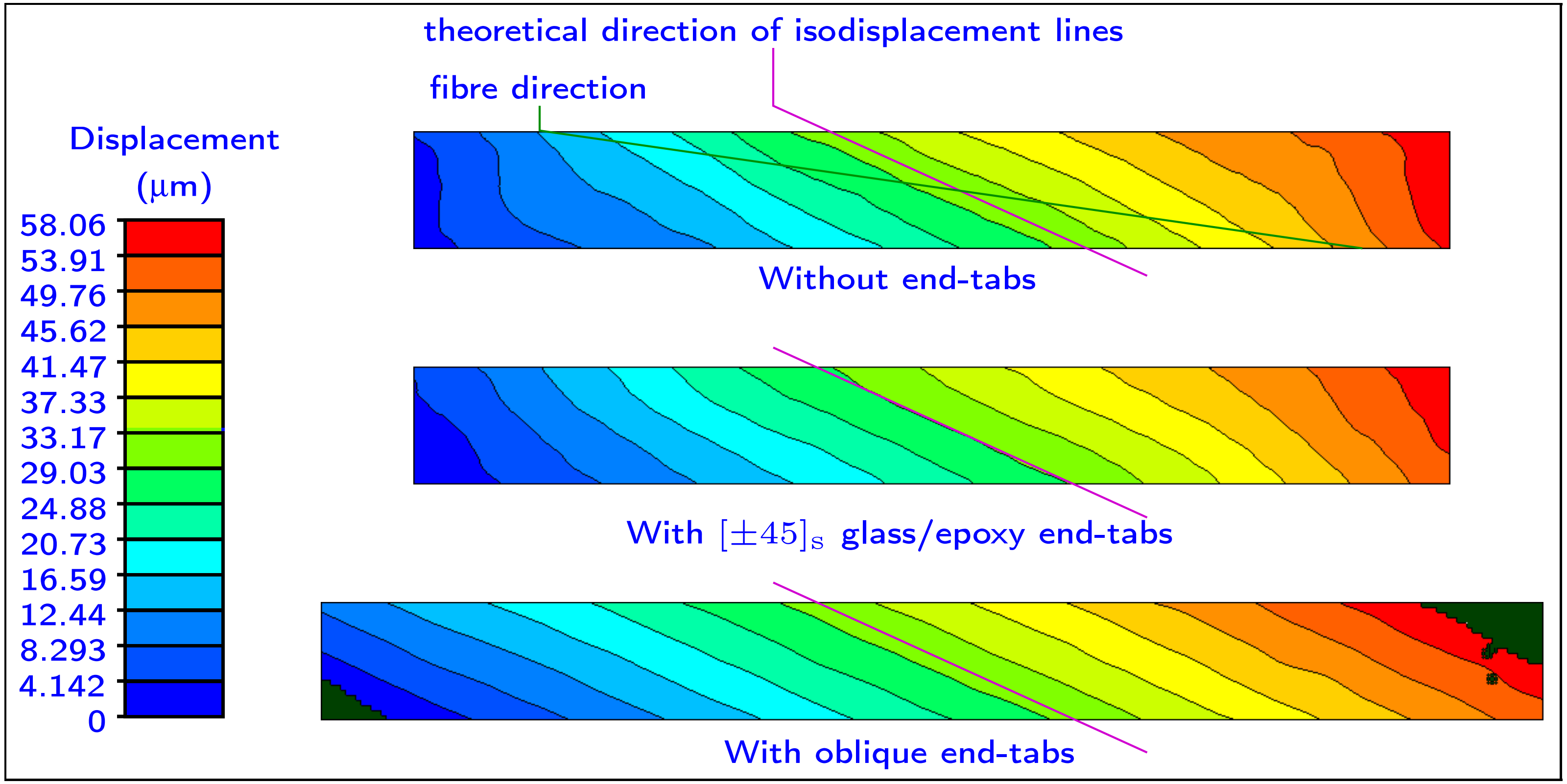


Figure 5: Off-axis tensile test on a unidirectional graphite/epoxy composite; $p = 610$ µm. Resolution evaluated from the noise amount: $2\pi/500$ or 1.2 µm. Axial displacement.

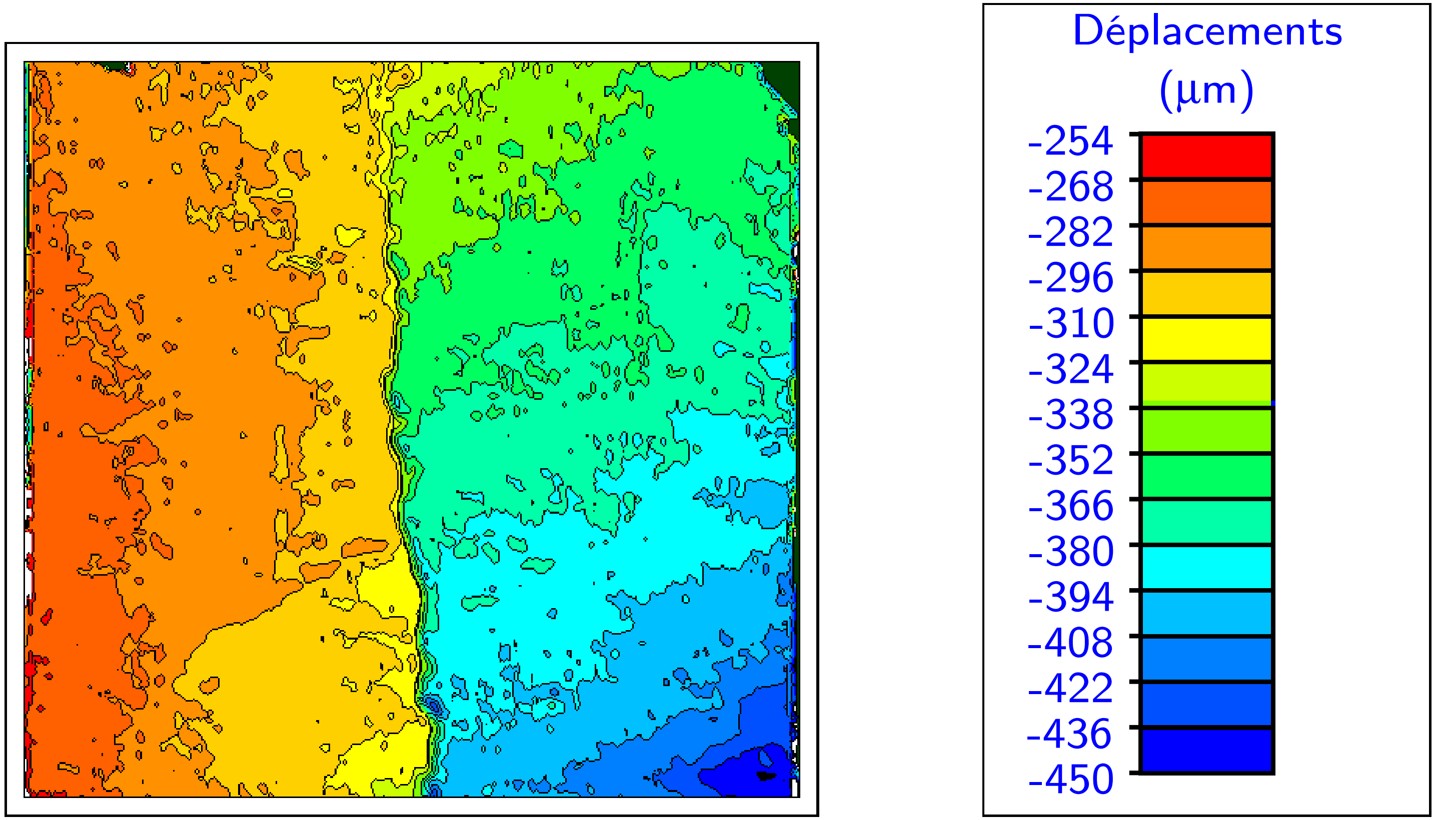
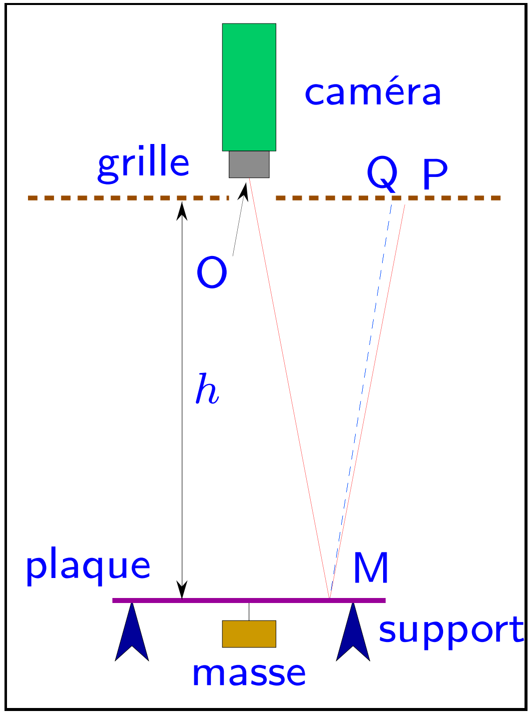
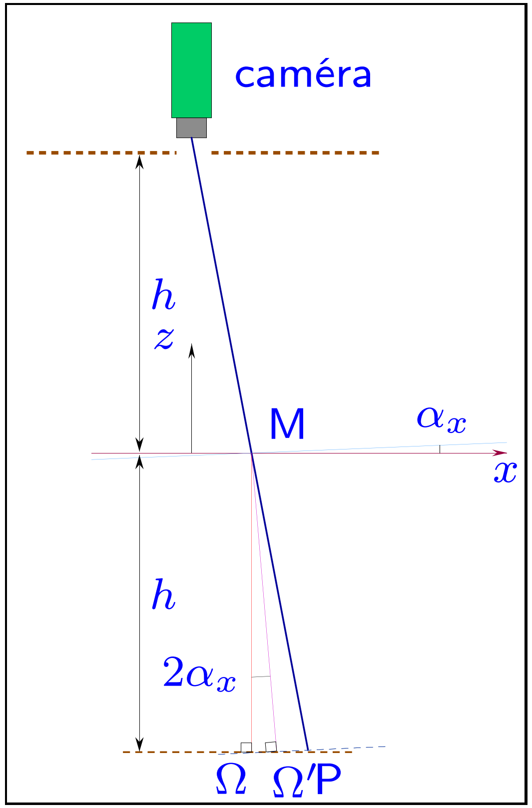


Figure 6: Crack propagation in reinforced concrete (100 mm $\times$ 100 mm area, $p = 500$ µm). 4-point bending. Horizontal displacement

2.2.2 Examples: slope measurements



(a) Principle



(b) Image rotation

Figure 7: Deflectometry

PMMA plate loading conditions:

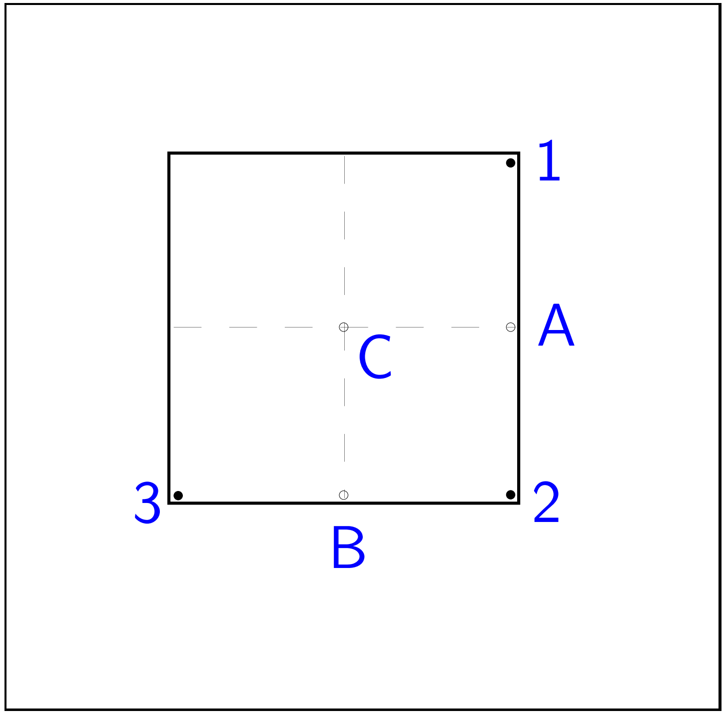
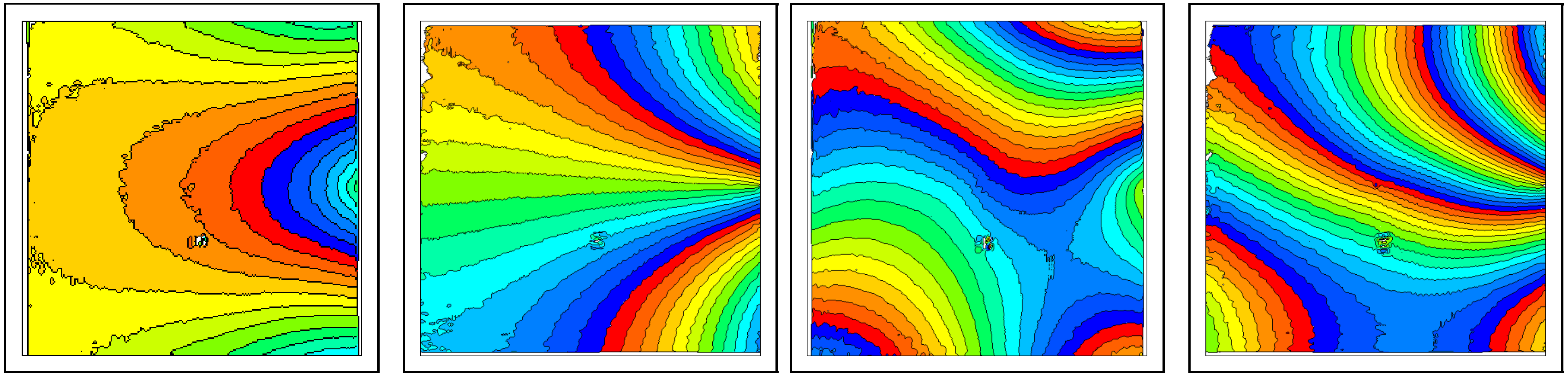
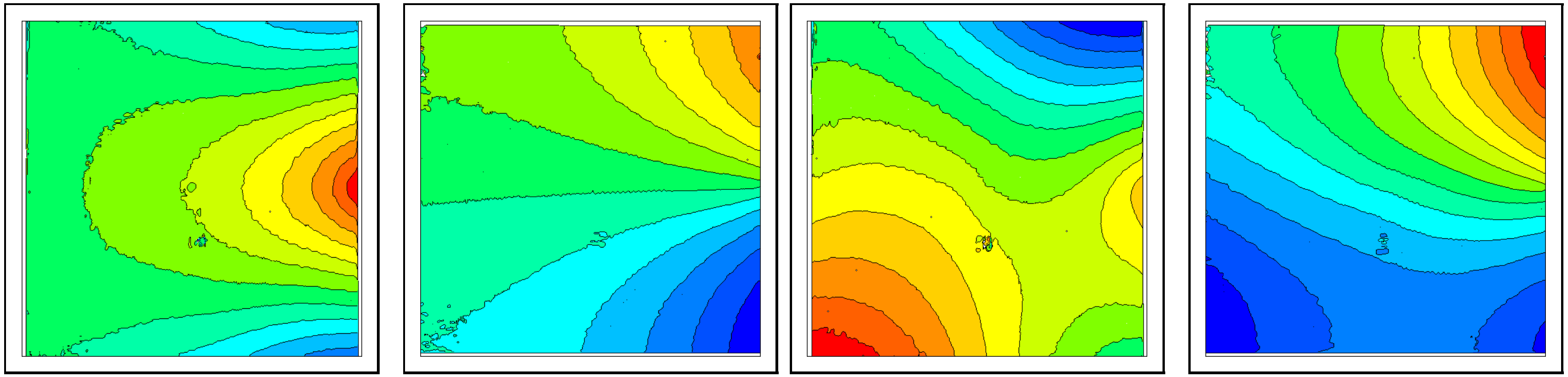


Figure 8: Loading of the plate: simple support at points 1, 2 and 3, and mass suspension at points A, B or C (90.9 g)

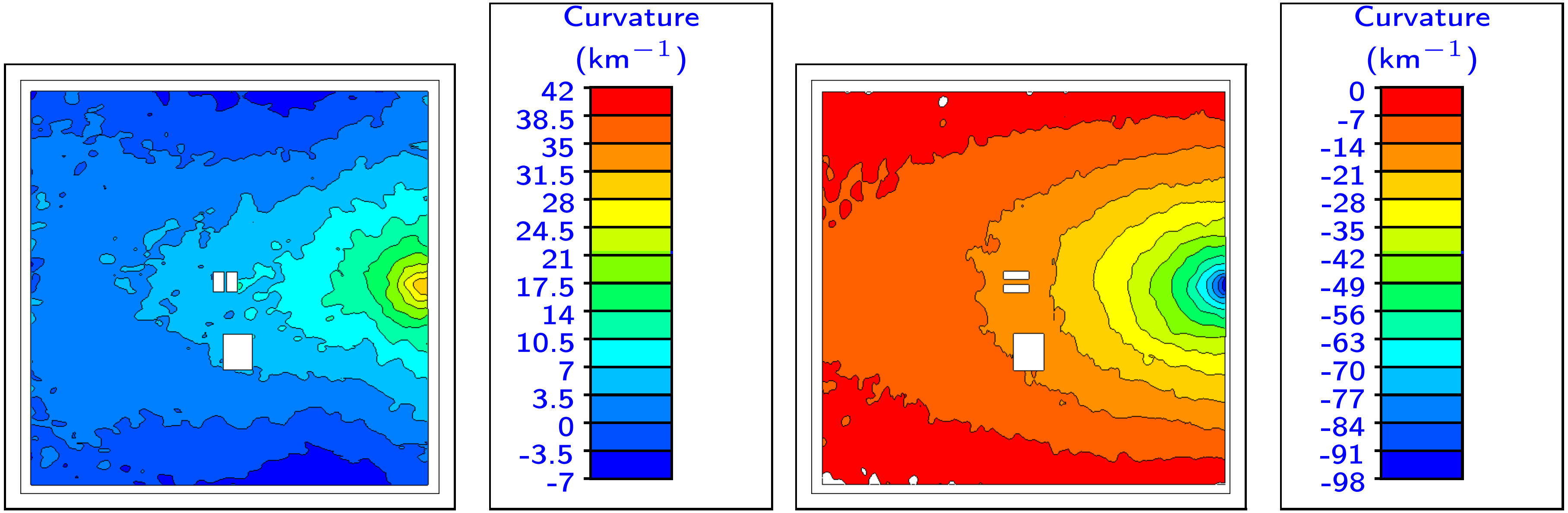


(a) ϕ_x, A (b) ϕ_y, A (c) ϕ_x, A + C (d) ϕ_y, A + C



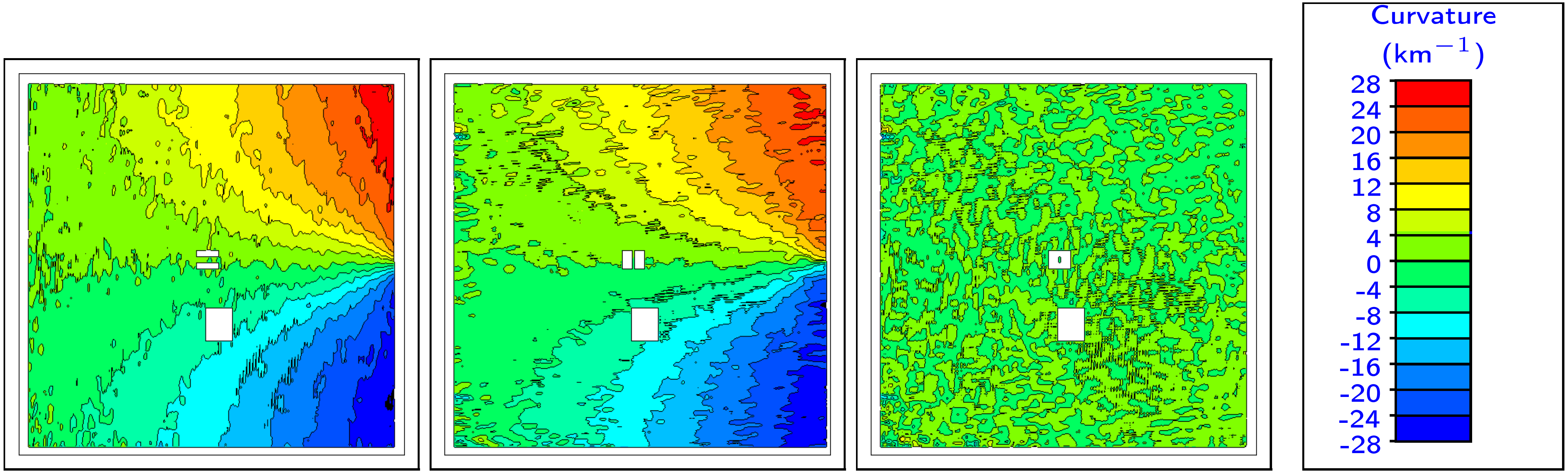
(e) ϕ_x, A (f) ϕ_y, A (g) ϕ_x, A + C (h) ϕ_y, A + C

Figure 9: Wrapped and unwrapped phase maps, proportional to slopes



(a) xx-curvature (b) yy-curvature

Figure 10: Curvatures; loading at point A



(a) xy-curvature (b) yx-curvature (c) Deviation ($\sigma = 1.25$ km^{-1})

Figure 11: Curvatures; loading at point A

2.2.3 Shape measurement

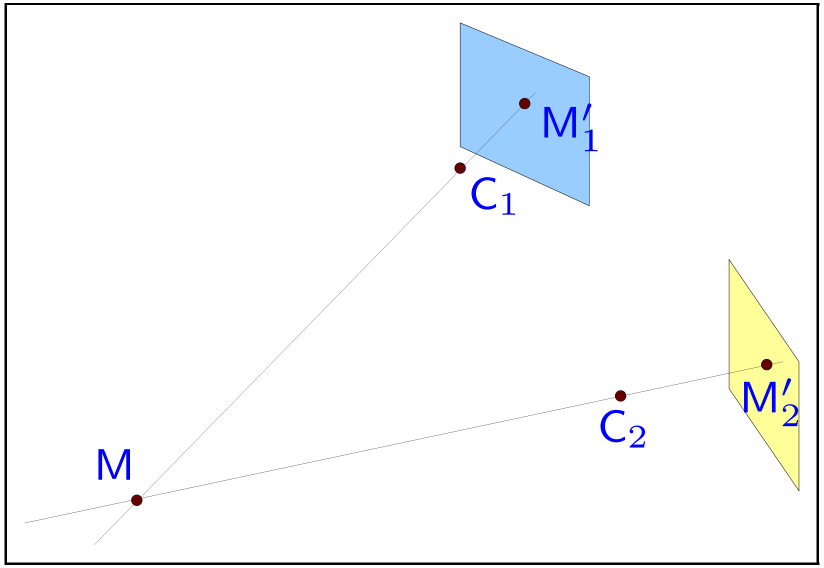


Figure 12: Shape measurement using stereocorrelation or fringe projection

- stereocorrelation: qualitative information go from M to M'_1 and M'_2; given any M'_1, the software must find the matching M'_2;
- fringe projection: quantitative information go from M'_1 to M, then from M to M'_2. The (unwrapped) phase value gives the matching.

2.2.3 Shape measurement

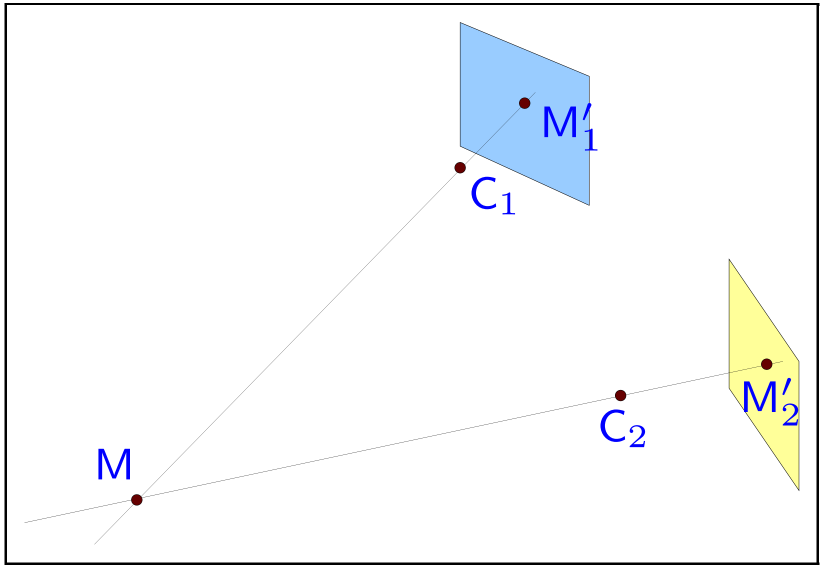


Figure 12: Shape measurement using stereocorrelation or fringe projection

- stereocorrelation: qualitative information go from M to M'_1 and M'_2; given any M'_1, the software must find the matching M'_2;
- fringe projection: quantitative information go from M'_1 to M, then from M to M'_2. The (unwrapped) phase value gives the matching.

2.3 Discussion

- most techniques exist under both dual implementations (periodic, random); their *names* should be related;
- *performances are better* with a periodic encoding (efficient phase detection); better to use a single frequency carrier than to use noise; typical:
  - ✓ 1/50 pixel resolution (provable), 5 pixels spatial resolution (carrier);
  - ✓ 1/50 pixel resolution (questionable), 32 pixels spatial resolution;
- carriers are *easier to characterize* (frequency, amplitude, SNR) than random patterns. . .
- carrier-based methods: more difficult, more expensive;
- problem with periodic carriers: periodic information (phase unwrapping may be necessary; nontrivial problem).

2.3 Discussion

- most techniques exist under both dual implementations (periodic, random); their *names* should be related;
- *performances are better* with a periodic encoding (efficient phase detection); better to use a single frequency carrier than to use noise; typical:
  - ✓ 1/50 pixel resolution (provable), 5 pixels spatial resolution (carrier);
  - ✓ 1/50 pixel resolution (questionable), 32 pixels spatial resolution;
- carriers are *easier to characterize* (frequency, amplitude, SNR) than random patterns. . .
- carrier-based methods: more difficult, more expensive;
- problem with periodic carriers: periodic information (phase unwrapping may be necessary; nontrivial problem).

2.3 Discussion

- most techniques exist under both dual implementations (periodic, random); their *names* should be related;
- *performances are better* with a periodic encoding (efficient phase detection); better to use a single frequency carrier than to use noise; typical:
  - ✓ 1/50 pixel resolution (provable), 5 pixels spatial resolution (carrier);
  - ✓ 1/50 pixel resolution (questionable), 32 pixels spatial resolution;
- carriers are *easier to characterize* (frequency, amplitude, SNR) than random patterns. . .
- carrier-based methods: more difficult, more expensive;
- problem with periodic carriers: periodic information (phase unwrapping may be necessary; nontrivial problem).

2.3 Discussion

- most techniques exist under both dual implementations (periodic, random); their *names* should be related;
- *performances are better* with a periodic encoding (efficient phase detection); better to use a single frequency carrier than to use noise; typical:
  - ✓ 1/50 pixel resolution (provable), 5 pixels spatial resolution (carrier);
  - ✓ 1/50 pixel resolution (questionable), 32 pixels spatial resolution;
- carriers are *easier to characterize* (frequency, amplitude, SNR) than random patterns. . .
- carrier-based methods: more difficult, more expensive;
- problem with periodic carriers: periodic information (phase unwrapping may be necessary; nontrivial problem).

2.3 Discussion

- most techniques exist under both dual implementations (periodic, random); their *names* should be related;
- *performances are better* with a periodic encoding (efficient phase detection); better to use a single frequency carrier than to use noise; typical:
  - ✓ 1/50 pixel resolution (provable), 5 pixels spatial resolution (carrier);
  - ✓ 1/50 pixel resolution (questionable), 32 pixels spatial resolution;
- carriers are *easier to characterize* (frequency, amplitude, SNR) than random patterns. . .
- carrier-based methods: more difficult, more expensive;
- problem with periodic carriers: periodic information (phase unwrapping may be necessary; nontrivial problem).

2.3 Discussion

- most techniques exist under both dual implementations (periodic, random); their *names* should be related;
- *performances are better* with a periodic encoding (efficient phase detection); better to use a single frequency carrier than to use noise; typical:
  - ✓ 1/50 pixel resolution (provable), 5 pixels spatial resolution (carrier);
  - ✓ 1/50 pixel resolution (questionable), 32 pixels spatial resolution;
- carriers are *easier to characterize* (frequency, amplitude, SNR) than random patterns...
- carrier-based methods: more difficult, more expensive;
- problem with periodic carriers: periodic information (phase unwrapping may be necessary; nontrivial problem).

2.3 Discussion

- most techniques exist under both dual implementations (periodic, random); their *names* should be related;
- *performances are better* with a periodic encoding (efficient phase detection); better to use a single frequency carrier than to use noise; typical:
  - ✓ 1/50 pixel resolution (provable), 5 pixels spatial resolution (carrier);
  - ✓ 1/50 pixel resolution (questionable), 32 pixels spatial resolution;
- carriers are *easier to characterize* (frequency, amplitude, SNR) than random patterns. . .
- carrier-based methods: more difficult, more expensive;
- problem with periodic carriers: periodic information (phase unwrapping may be necessary; nontrivial problem).

3 Interferometric methods

Interference fringe intensity: $I = I_0(1 + \gamma \cos \Phi) = I_0[1 + \gamma \cos(\phi_2 - \phi_1)]$

Variation between two states:

$$\Delta\Phi = (\phi_2 - \phi_1)_\mathrm{f} - (\phi_2 - \phi_1)_\mathrm{i} = (\phi_\mathrm{f} - \phi_\mathrm{i})_2 - (\phi_\mathrm{f} - \phi_\mathrm{i})_1 = \Delta\phi_2 - \Delta\phi_1$$

For the beam(s) interacting with a moving surface: $\Delta\phi = (\vec{k}_\mathrm{e} - \vec{k}_\mathrm{o}).\vec{u} = \vec{g}.\vec{u}$

Sensitivity: depends on the setup. Rule of thumb: $2\pi \sim \lambda$.

Resolution: $2\pi/50$ routinely achieved.

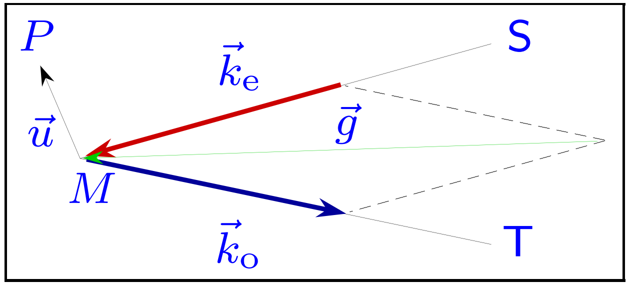
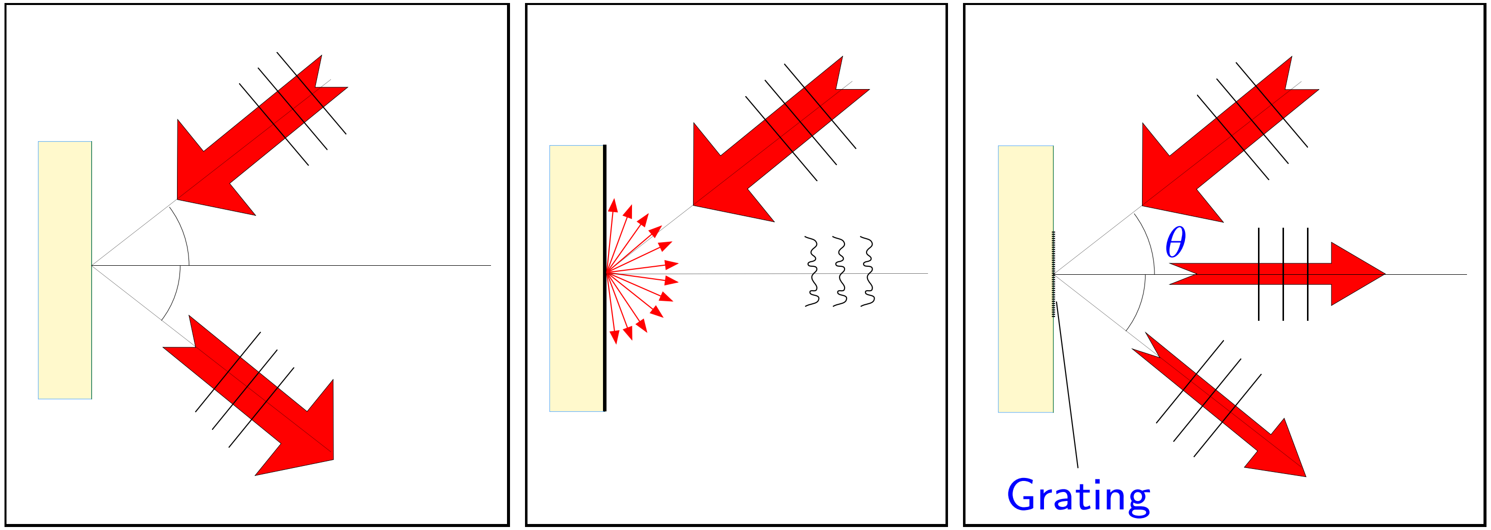


Figure 13: Sensitivity vector

3.1 Light-surface interactions



(a) Specular reflection

(b) Diffusion

(c) Diffraction

Figure 14: Different possibilities

Only (b) and 14(c) involve an in-plane component of the displacement.

3.2 Synthetic sensitivity vectors

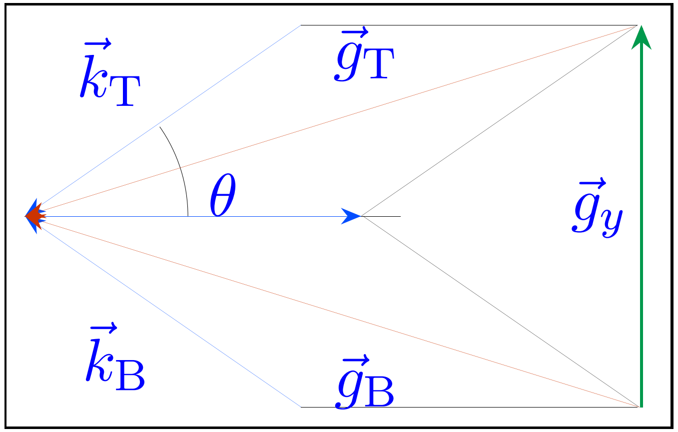
With N illumination directions:

$$\left\{ \begin{array}{rcl} \Delta\phi_0 & = & \vec{g}_0.\vec{u} \\ \Delta\phi_1 & = & \vec{g}_1.\vec{u} \\ & \cdots & \\ \Delta\phi_{N-1} & = & \vec{g}_{N-1}.\vec{u} \end{array} \right. \quad (1)$$

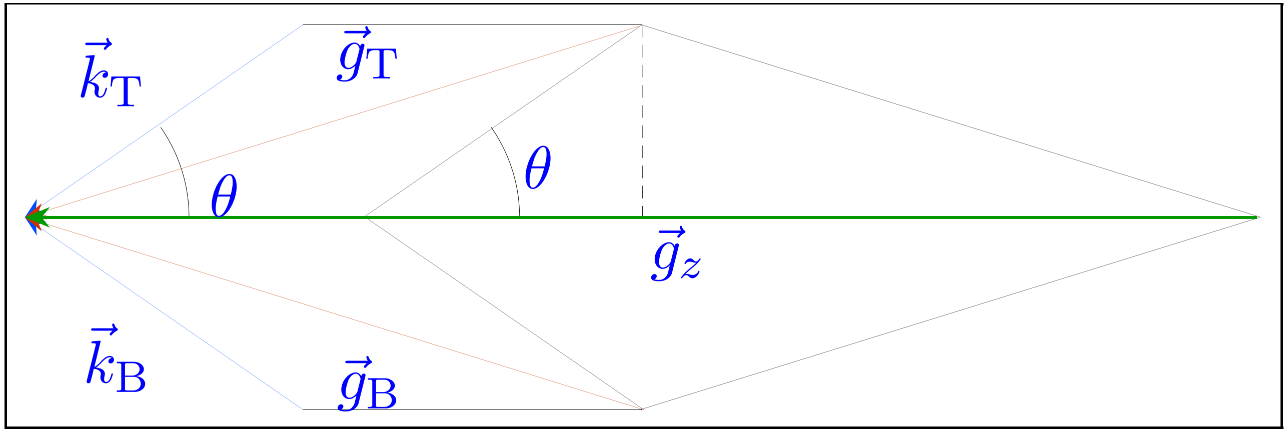
With simple linear combinations, one can create synthetic sensitivity vectors:

$$\sum_{i=0}^{N-1} \alpha_i \Delta\phi_i = \left(\sum_{i=0}^{N-1} \alpha_i \vec{g}_i \right) .\vec{u} = \vec{G}.\vec{u} \quad (2)$$

It is possible with symmetric vectors to create in-plane and out-of-plane synthetic sensitivity vectors



(a) Subtraction of sensitivity vectors



(b) Addition of sensitivity vectors

3.3 Different types of interferometry

3.3.1 Reference beam and test beam

Then $\Delta\Phi = \Delta\phi_{\mathrm{test}} - \Delta\phi_{\mathrm{ref}} = \Delta\phi_{\mathrm{test}} = \vec{g}.\vec{u}$: displacement component along $\vec{g}$.

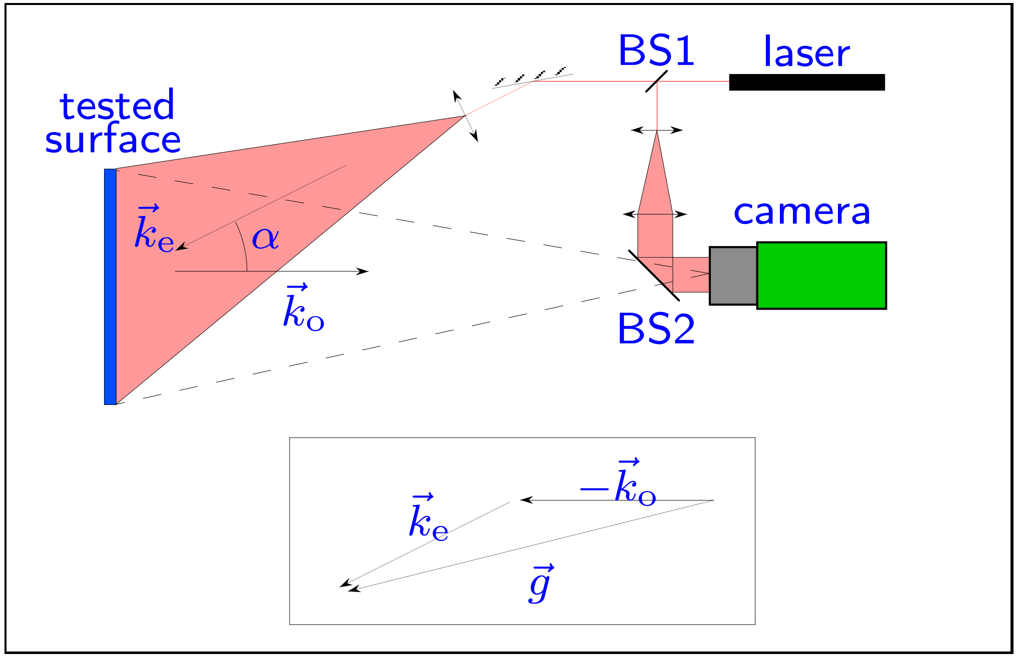


Figure 16: In-plane speckle interferometry

3.3.2 Two test beams at the same point with different sensitivity vectors

Then $\Delta\Phi = \Delta\phi_2 - \Delta\phi_1 = \vec{g}_2.\vec{u} - \vec{g}_1.\vec{u} = (\vec{g}_2 - \vec{g}_1).\vec{u} = \vec{G}.\vec{u}$.

Example with symmetric illumination:

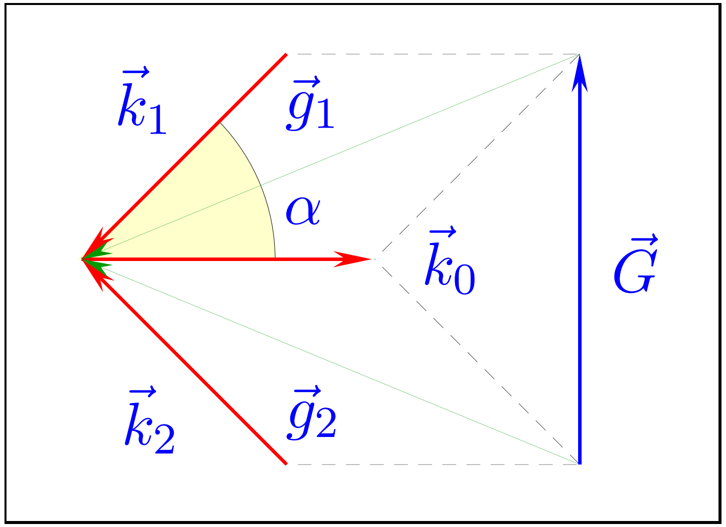


Figure 17: Sensitivity vectors

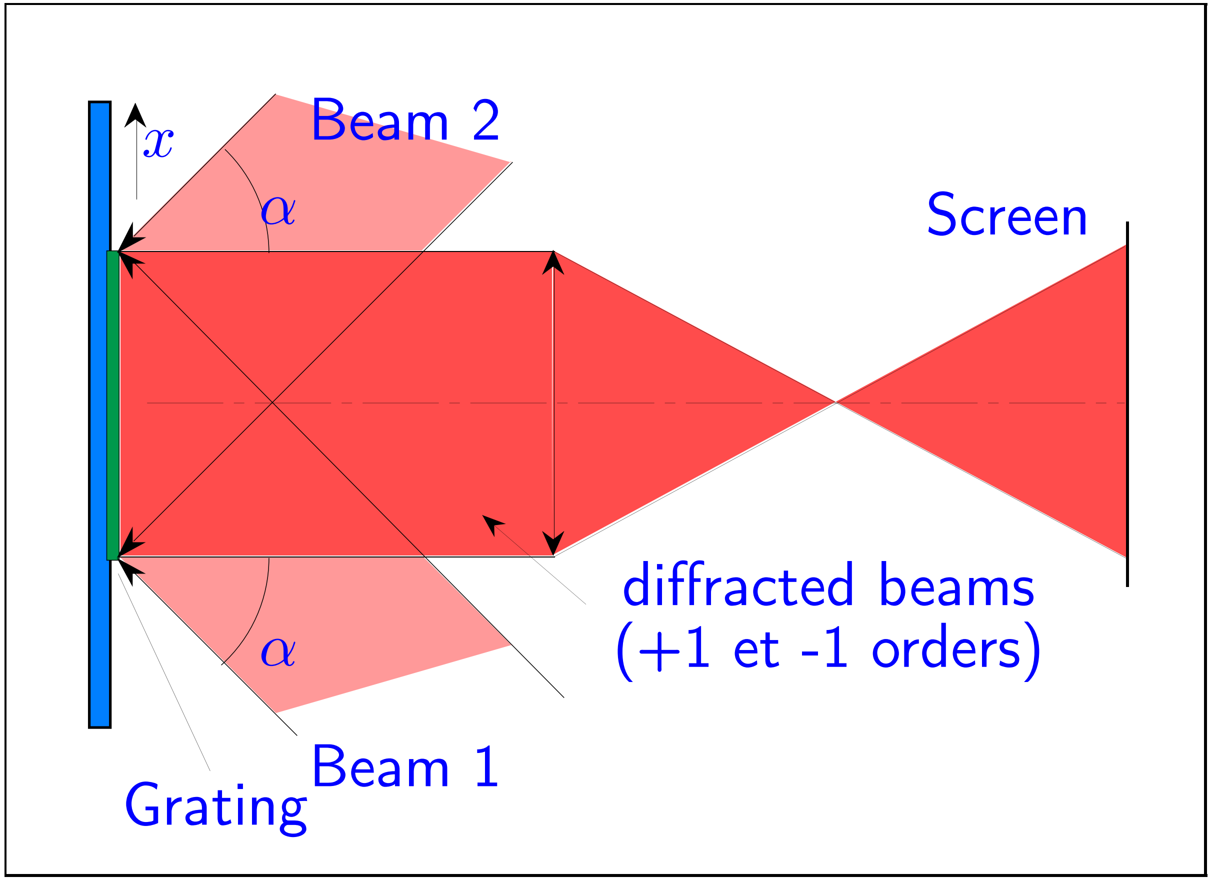
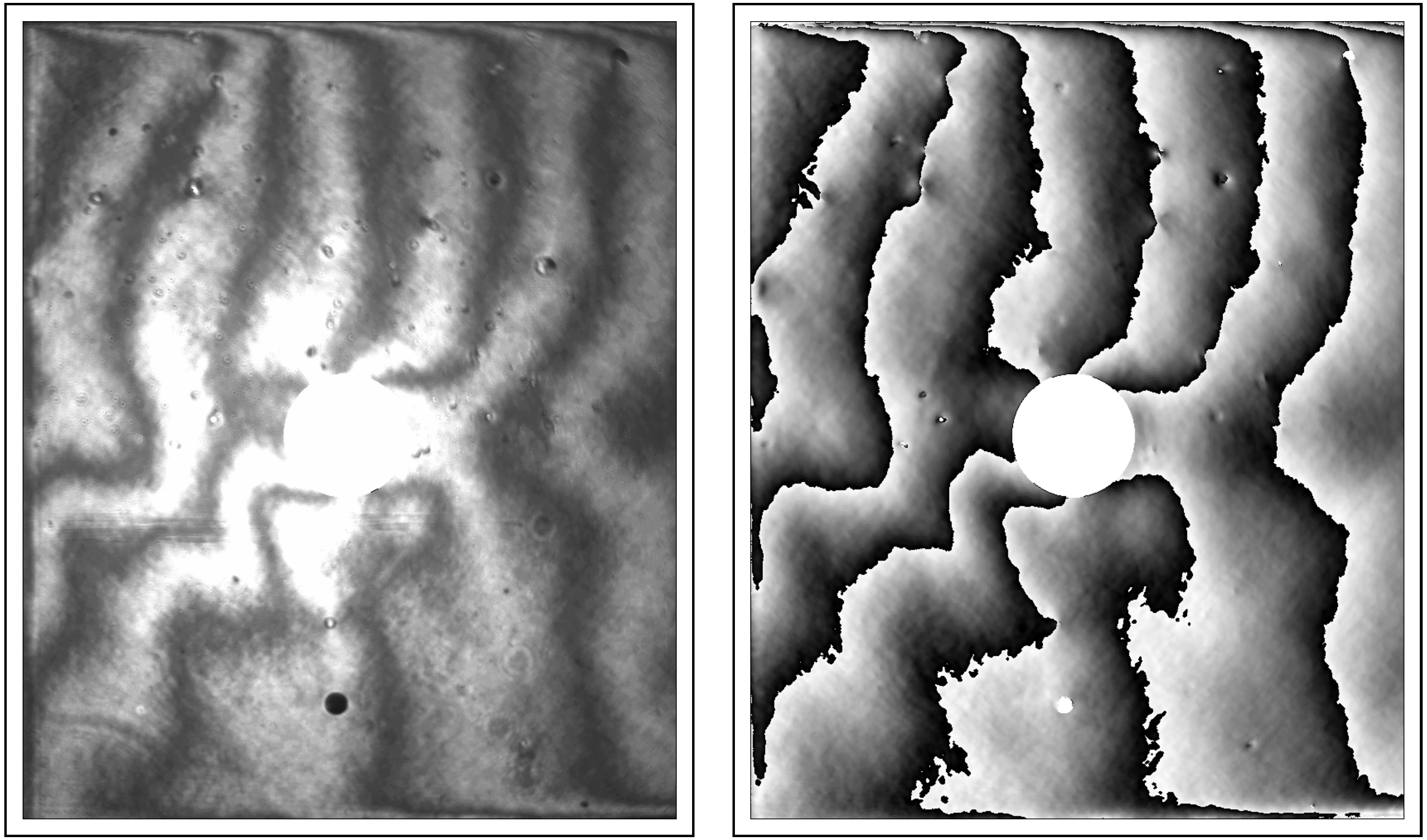
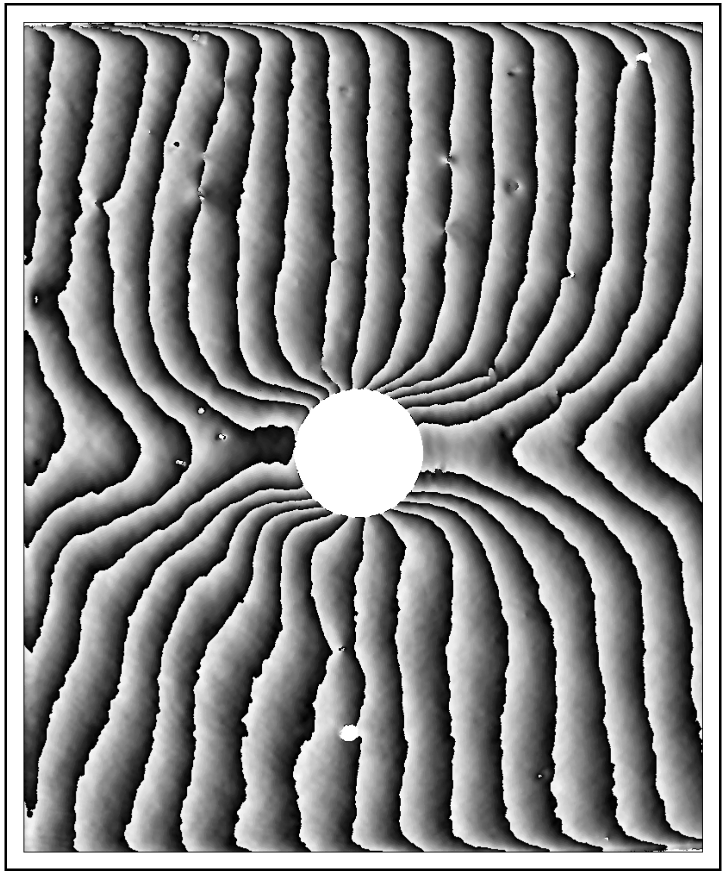


Figure 18: Interferometric moiré

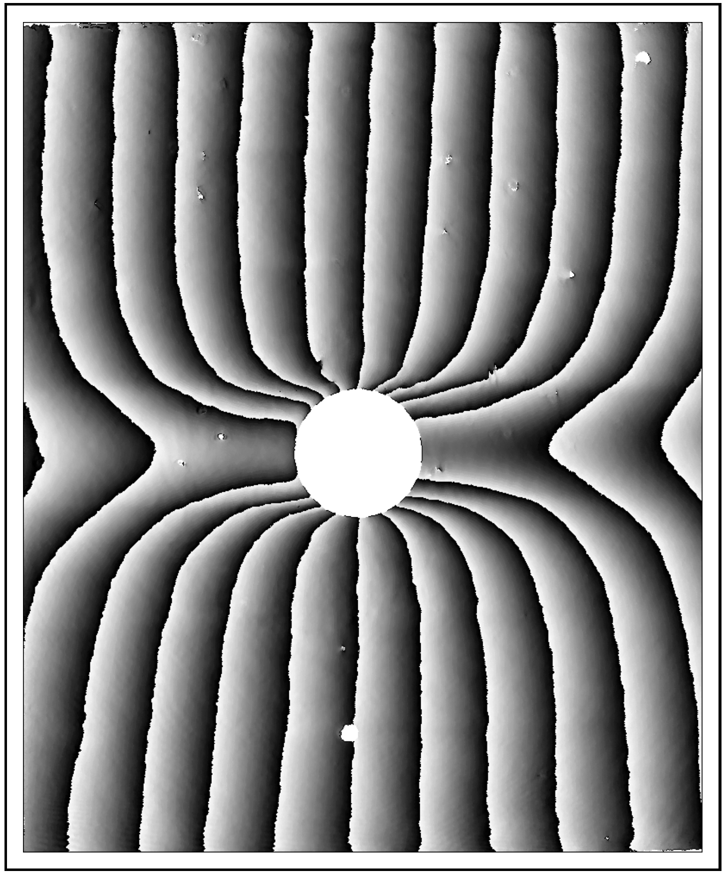


(a) Initial intensity (b) Initial phase

Figure 19: Horizontal tensile test on a composite specimen with a 4 mm hole. Initial state. [J.-R. Lee, ENSMSE]



(a) Final phase



(b) Displacement u_x

Figure 20: Horizontal tensile test on a composite specimen with a 4 mm hole. Final state. No smoothing. [J.-R. Lee, ENSMSE]

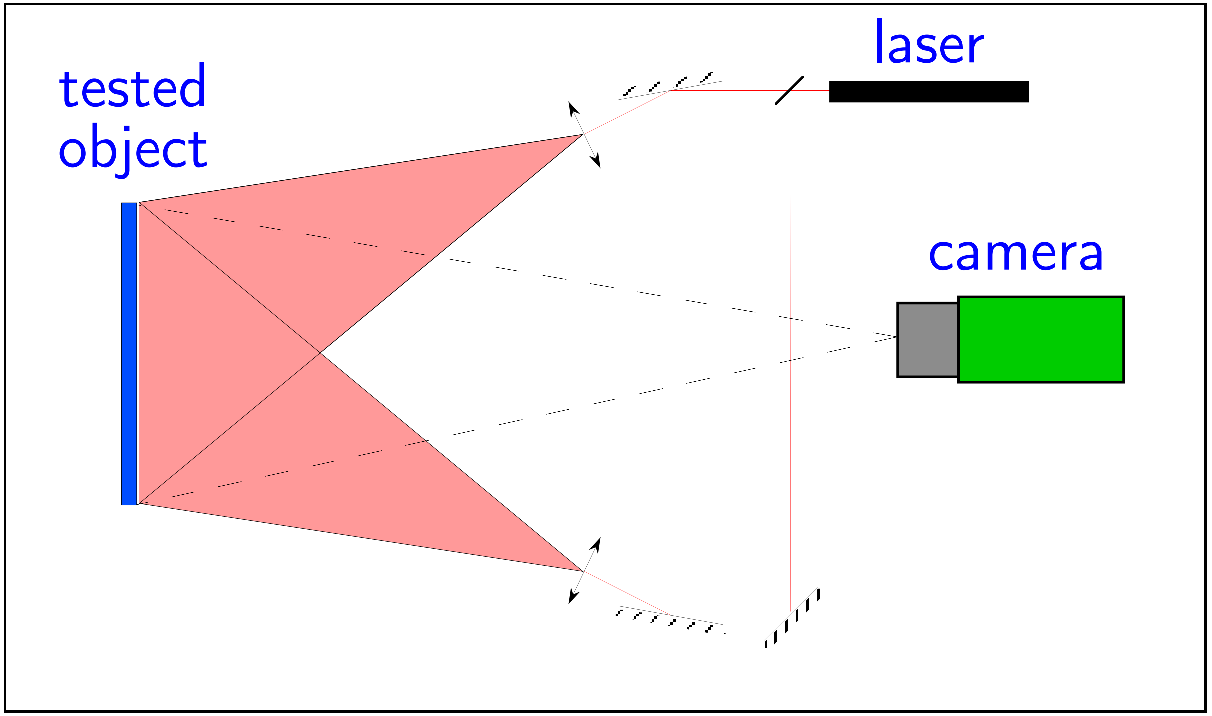


Figure 21: In-plane speckle interferometry

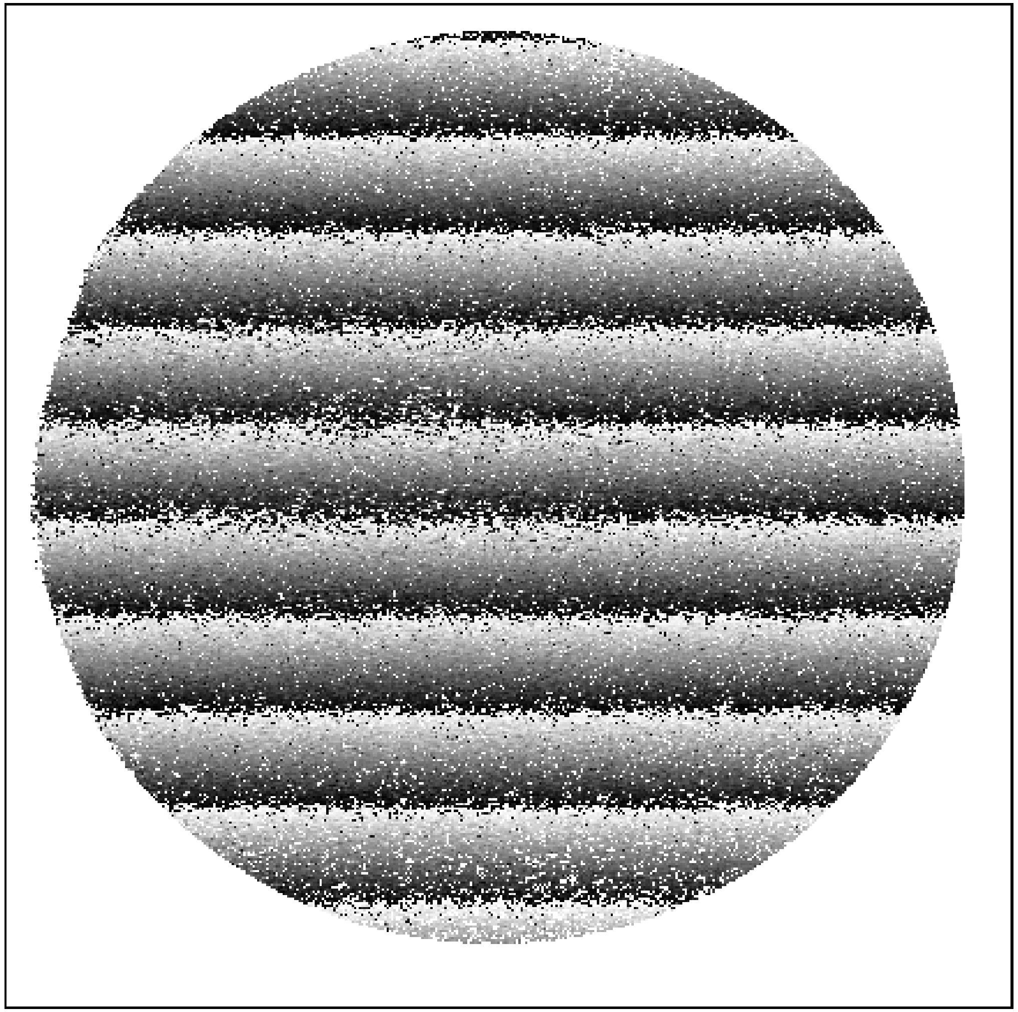


Figure 22: u_x field during a rotation

3.3.3 Two laterally shifted beams

Then $\Delta\Phi = \Delta\phi_2 - \Delta\phi_1 = \vec{g}.(\vec{u} + \delta\vec{u}) - \vec{g}.\vec{u} = \vec{g}.\delta\vec{u}$. Insensitive to vibrations!

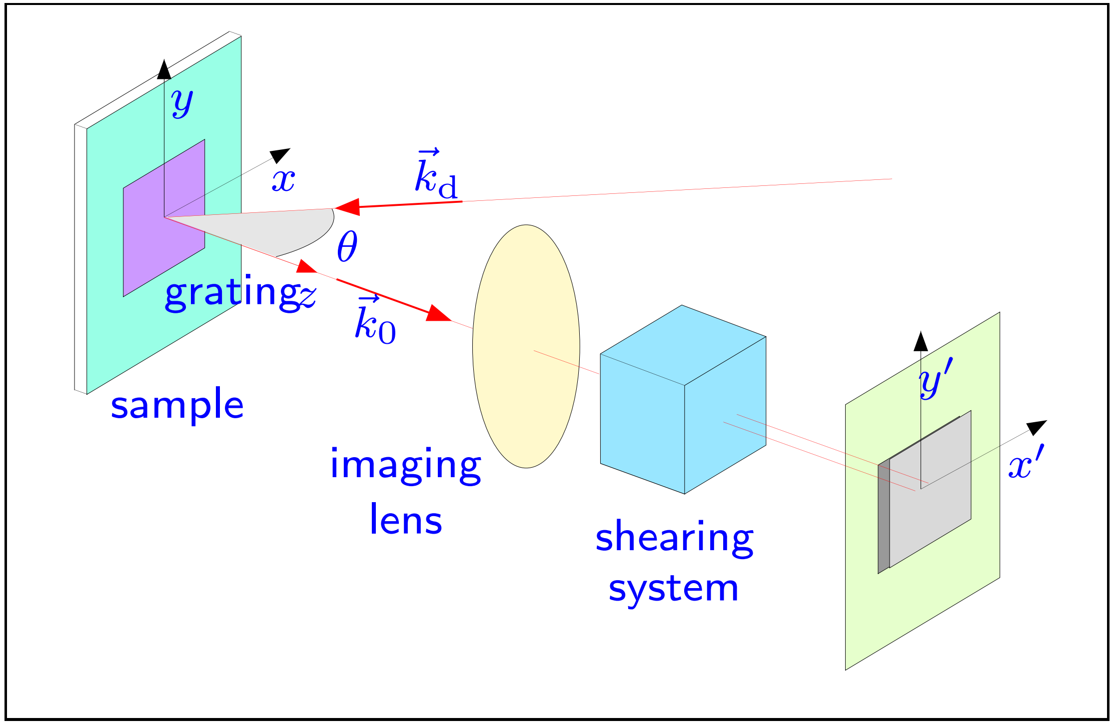


Figure 23: Grating shearography (differential interferometry in diffused light)

With two shear directions and four illumination directions (top, bottom, left and right), all components of strain as well as slopes are measured.

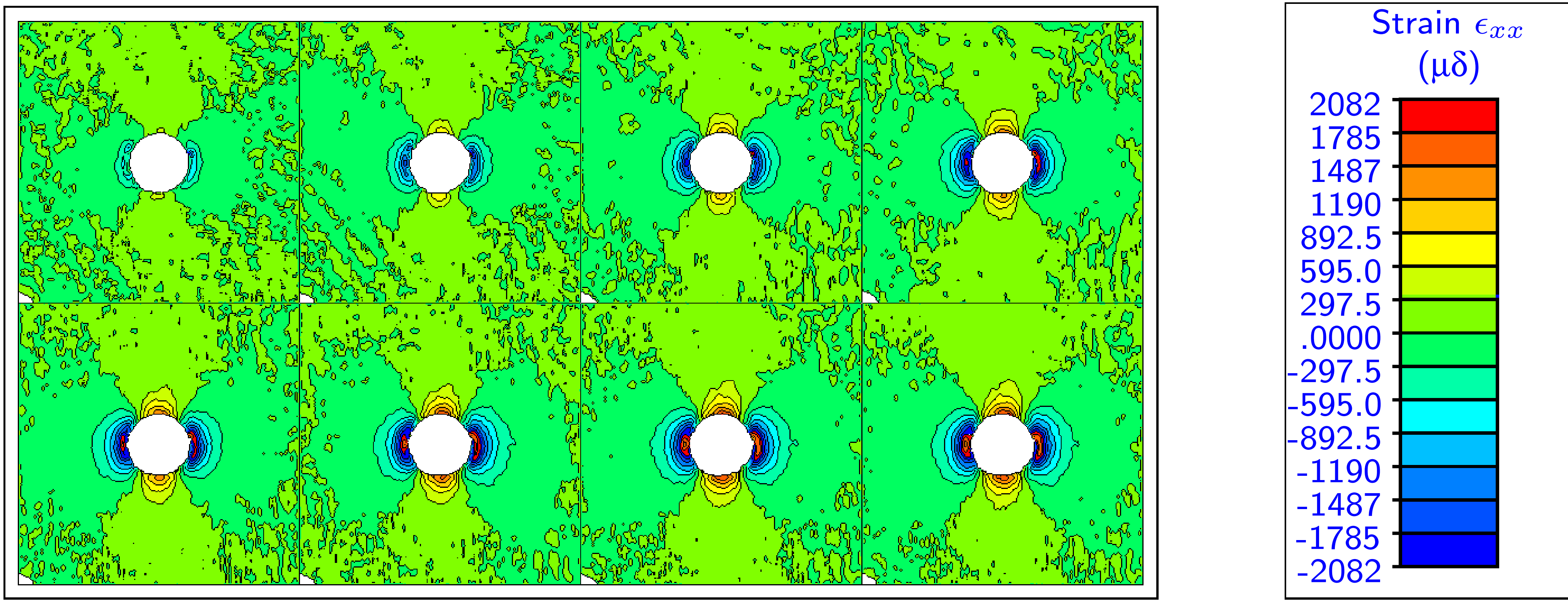


Figure 24: Residual stress in aluminium, incremental hole-drilling method. Strain ϵ_{xx}

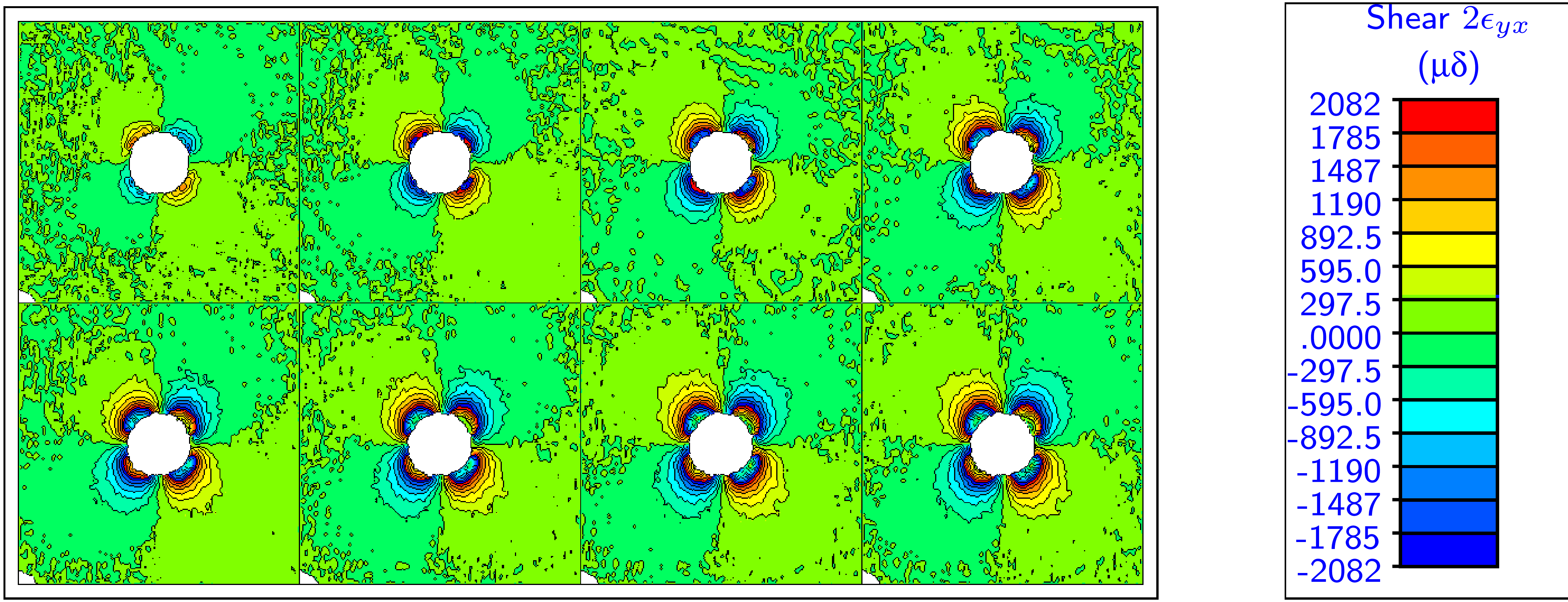


Figure 25: Residual stress in aluminium, incremental hole-drilling method. Shear strain $2\epsilon_{xy}$

4 Summary

White light			
Measurand	Random encoding	Phase encoding	Remarks
In-plane displ.	image correlation	Grid (with/out moiré)	Coupling with out-of-plane
Shape	Stereocorrelation	fringe projection (structured light)	Distorsion correction essential
3D displ.	Stereocorrelation (attached speckle)	Impossible	id.
Slopes	Not used	Deflectometry	Coupling with shape

Interferometry			
Measurand	Refl. light	Diffus. light	Diffrac. light
In-plane displ.	Impossible	In-plane speckle	Interferometric moiré
Out-of-plane displ.	Interferometry MICHELSON-TWYMANN-GREEN	Out-of-plane speckle	unused
Differential setup (slopes, strains)	e.g. Nomarski microscopy	Shearography	Grating shearography

Table 1: Performances

	White light, random	White light, phase	Interferometry
Ease of use	++	+	−
Cost	−−	−	+
Performances	−	−+	++

5 Conclusion

- OFFMT can be strictly sorted using single concepts: white or monochromatic light, random or carrier encoding, light-surface interaction, proper understanding of interfering beams.
- Terminology is messy. Completely different names refer to techniques which are the same (ESPI, TV-holography) or closely connected (grid method, moiré). On the contrary, close names (speckle correlation, speckle interferometry) refer to conceptually different techniques.
- For metrological issues, carrier-based techniques are better in principle: better characterization, better resolution.

5 Conclusion

- OFFMT can be strictly sorted using single concepts: white or monochromatic light, random or carrier encoding, light-surface interaction, proper understanding of interfering beams.
- Terminology is messy. Completely different names refer to techniques which are the same (ESPI, TV-holography) or closely connected (grid method, moiré). On the contrary, close names (speckle correlation, speckle interferometry) refer to conceptually different techniques.
- For metrological issues, carrier-based techniques are better in principle: better characterization, better resolution.

5 Conclusion

- OFFMT can be strictly sorted using single concepts: white or monochromatic light, random or carrier encoding, light-surface interaction, proper understanding of interfering beams.
- Terminology is messy. Completely different names refer to techniques which are the same (ESPI, TV-holography) or closely connected (grid method, moiré). On the contrary, close names (speckle correlation, speckle interferometry) refer to conceptually different techniques.
- For metrological issues, carrier-based techniques are better in principle: better characterization, better resolution.